Service Life Extension of the ISS Propulsion System

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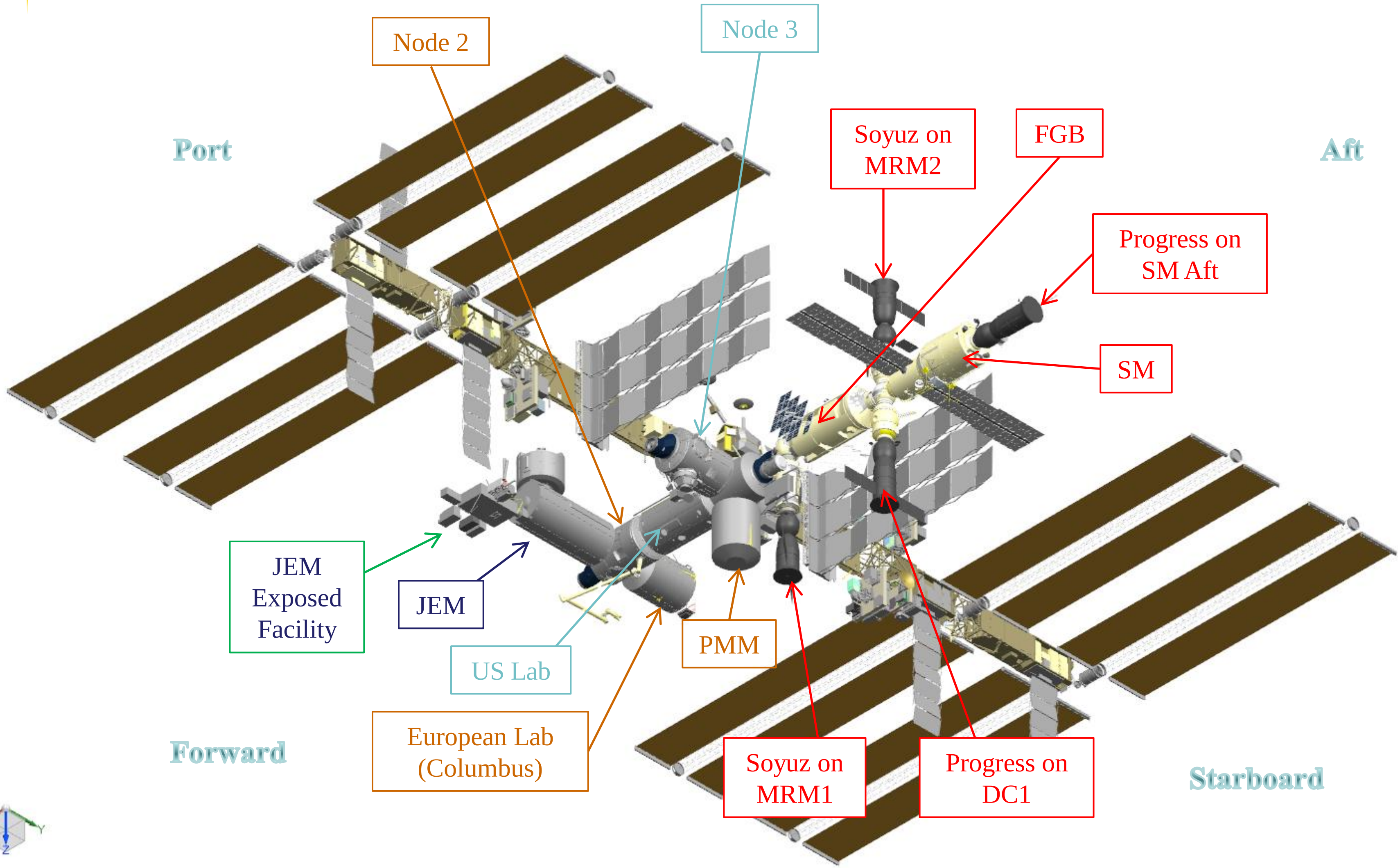
International Space Station



Functional Cargo Block

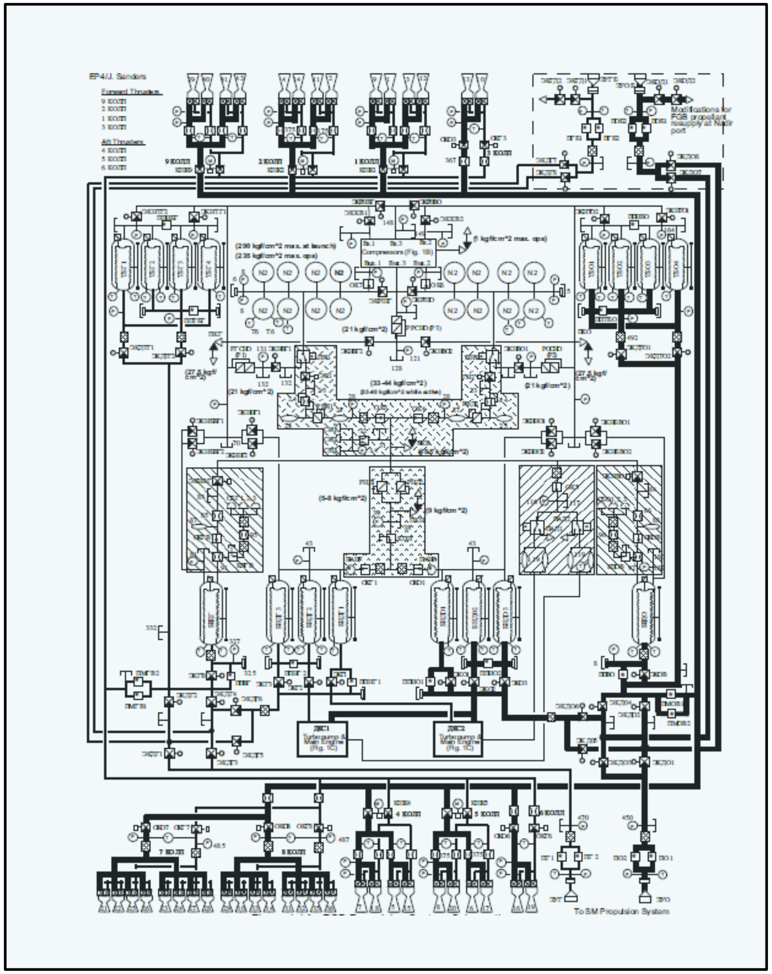
- First ISS Element
- Known by its Russian acronym FGB
- U.S. owned Russian Module
- Used primarily for cargo and propellant storage

Length	12.99 m
Maximum diameter	4.1 m
Mass	24,968 kg
Pressurized volume	71.5 m^3
Solar array span	24.4 m
Array surface area	28 m^2
Power supply (avg.)	3 kW
Propellant mass	3,800 kg
Launch date	20-Nov-98

- Two docking interfaces that support propellant transfer

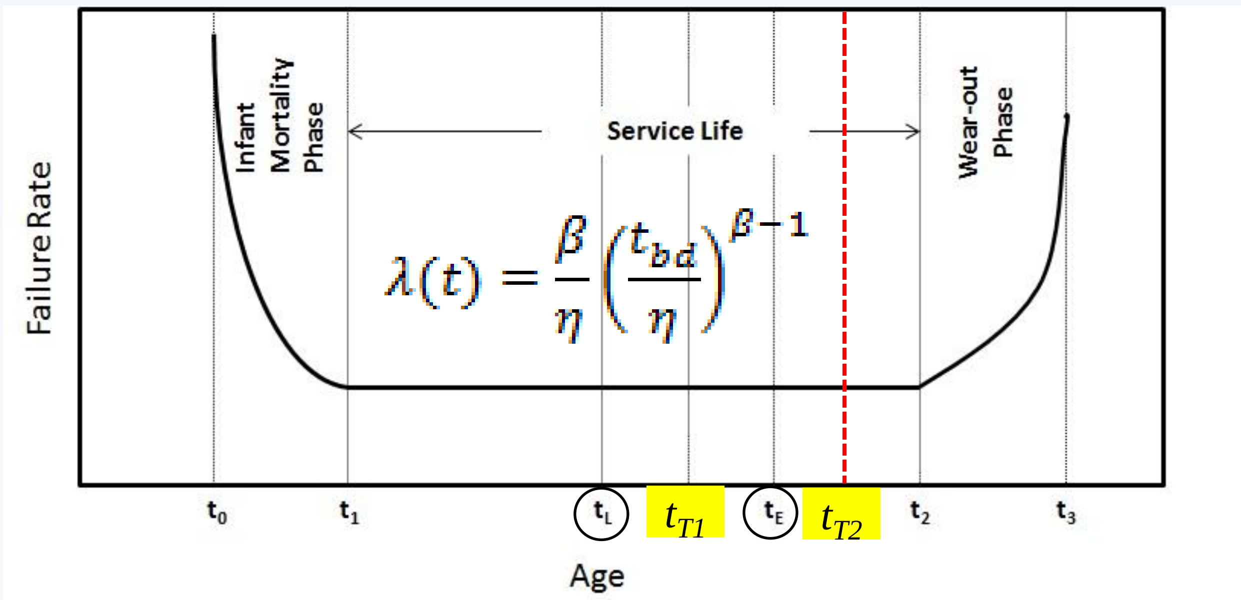
FGB Propulsion System

- Stores ~6 MT propellants
- Feeds SM/Progress thrusters
- Refueled by Progress/ATV
- Over 200 components:
  - 16 propellant tanks,
  - 16 pressurant tanks,
  - 42 thrusters,
  - 3 compressors,
  - 14 check valves,
  - 9 safety relief valves,
  - 32 pyrotechnic valves,
  - 7 pressure regulators, and
  - Over 70 isolation valves.



Service Life Extension

Hypothetical Bath Tub Curve



- Failure rate as a function of time:
  - Decreases with time when $\beta < 1$
  - Increases with time when $\beta > 1$
  - Constant failure rate when $\beta = 1$

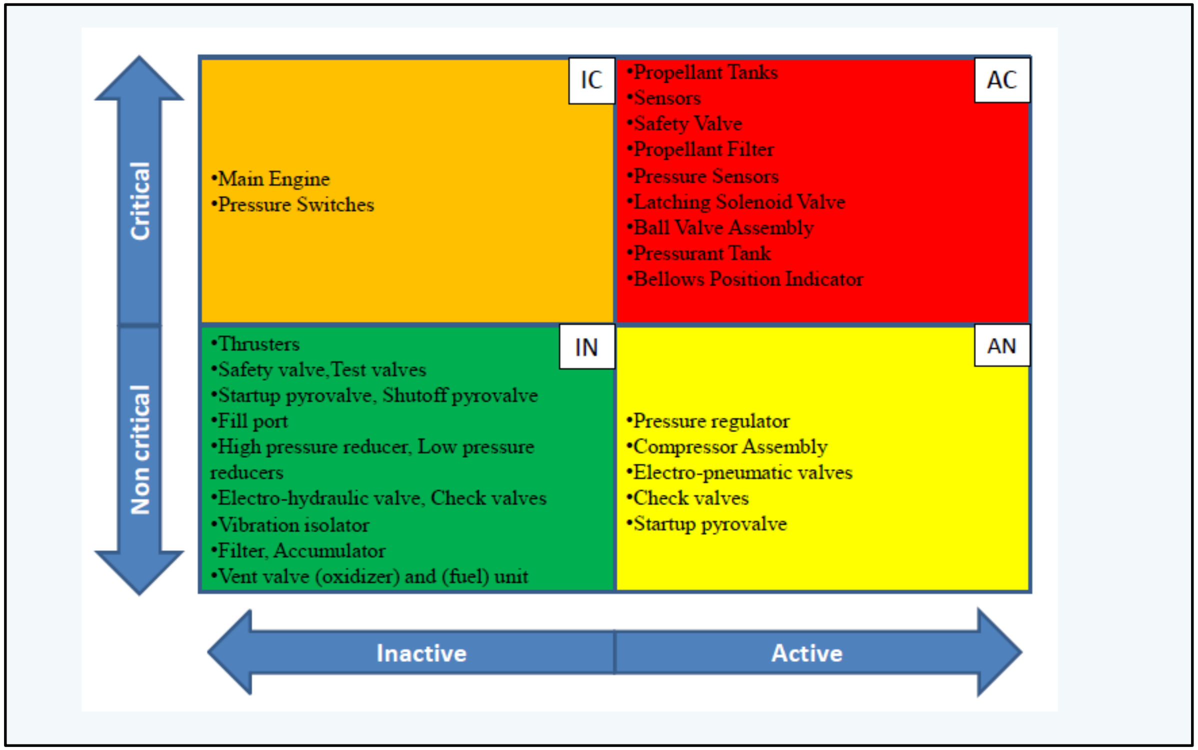
t_{bd} = time to break down; β and η are shape and scale factors of Weibull PDF

- Additional testing to t_{T2} allows extension from initial certified life, t_L to t_E
- Factor of Safety (FOS) remains unchanged

$$FOS = \frac{(t_{T1} - t_1)}{(t_L - t_1)} = \frac{(t_{T2} - t_1)}{(t_E - t_1)}$$

Optimization

- Selection based on failure modes and criticality
  - ➢ Systems used for propellant storage/transfer
  - ➢ Systems isolated but critical
  - ➢ Less critical active systems
- Hazard analysis
- Redundant systems
- Fault tolerance



Arrhenius Model

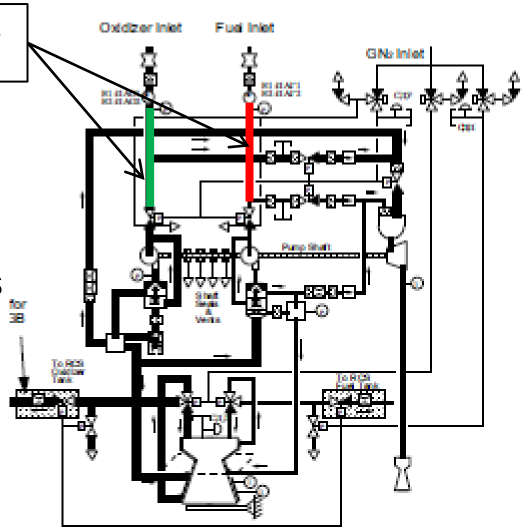
$$\alpha = \frac{t_T}{t_L} \propto e^{\left[\frac{1}{T_T} - \frac{1}{T_L}\right]}$$

α = **Acceleration Factor**
t_T = **Test Duration**
t_L = **Component Life**
T_T = **Average Temperature during Test**
T_L = **Average Temperature during Ops**

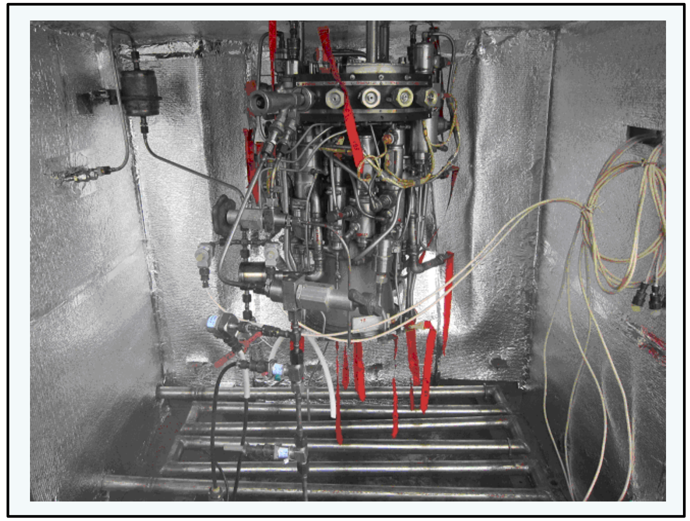
- Components with demonstrated cycle life margin
- Single test for multiple units on the fleet leader
- Accelerated Life Test (ALT)
  - ➢ Selected materials, parts and soft goods
  - ➢ Arrhenius model simulates corrosion with propellant exposure

Main Engine

Line segments with trapped propellants



- Structural/leakage integrity
  - ➢ Engines were isolated 2 years after FGB was launched.
  - ➢ Trapped propellants pose corrosion concern.

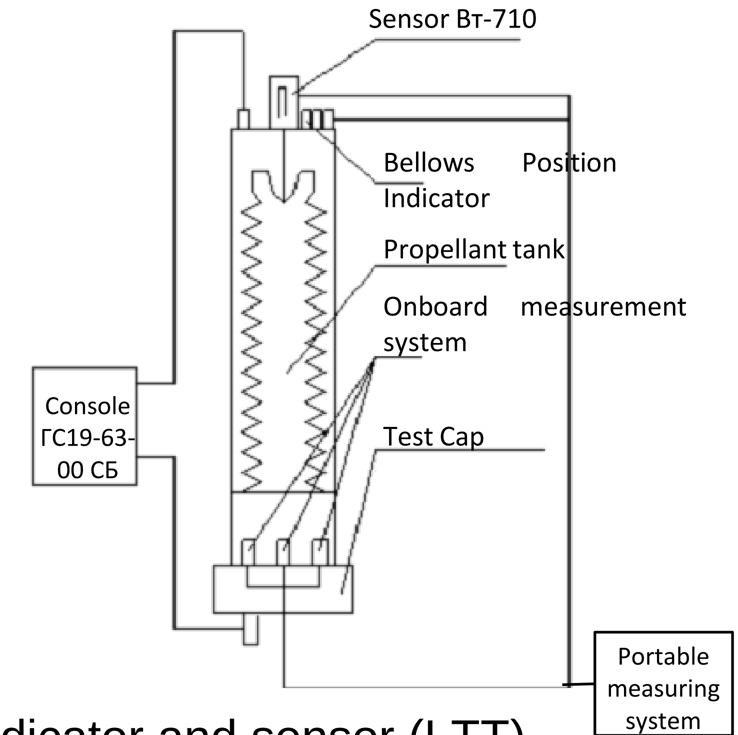


- Accelerated Life Test (ALT) of Main Engine
  - Inlet line filled with 3.5 liter of N_2O_4 at 0.3 MPa and 323 K
  - ALT duration = 225 days
  - Passed leakage integrity and defect analysis
  - Unit cleared for FGB service life until 2028.

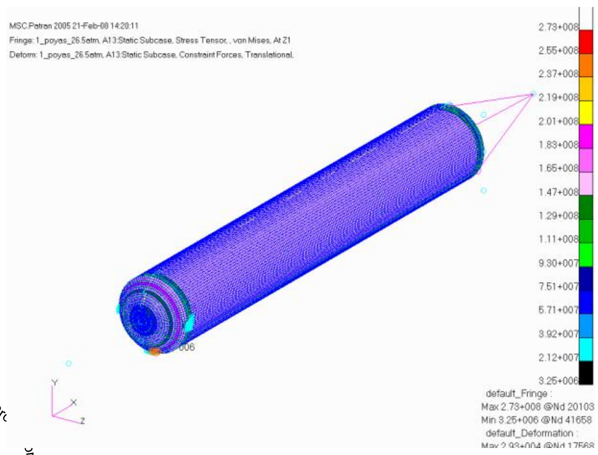
Propellant Tank

- Bellows cycle life
  - Demonstrated 111 cycles on multiple tanks

Start of Operating Period	End of Operating Period	Number of Years	Expected Cycles per year	Expected Cycles over period	Safety Factor	Test Cycles Applied
1998	2013	15	2	30	1.5	45
2013	2020	7	4	28	1.5	42
2020	2028	8	2	16	1.5	24
Cumulative		30		74	1.5	111



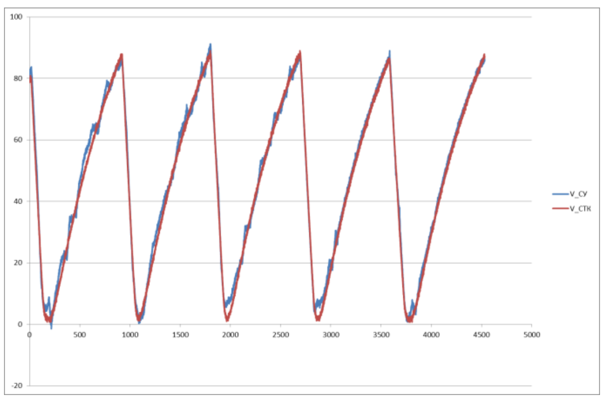
- Structural integrity verified by FEM
  - Al-Mg3 shell, stainless steel bellows



- Bellows position indicator and sensor (LTT)
  - Accelerated aging with propellant exposure
  - Mounted in test chambers filled with 50 mg/m^3 propellant vapor concentration at 0.11 MPa and 323 K
  - LTT failed when exposed to worst case N_2O_4 concentration beyond 26 years (ALT)
  - Risk accepted by NASA due to low probability failure mode.

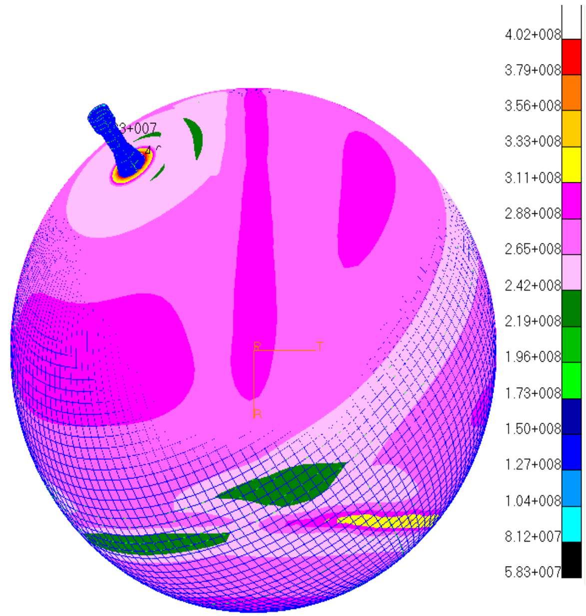
D-Unit Testing

- Simultaneous testing of multiple components
  - 32 cycles on pressure sensor, pressure indicator, GN_2 tank, safety valve, solenoid valve and the ball valve.
- De-mineralized water transferred between two propellant tanks
  - Simulated propellant transfer to/from the FGB tanks
  - Accumulated 111 bellows cycles
  - Forward/reverse flow across propellant filter
- Accelerated aging of multiple components
  - Ball valve, filter, safety valve…
  - Nominal results after ALT and defect analysis



Pressurant Tank

- FGB has 16 high pressure GN_2 storage tanks arranged in 2 functionally redundant sections
- Classified as Active -Critical (AC) component based on SLE optimization
- 32 pressure cycles added on the D-Unit GN_2 tanks
- FEM performed to assess structural integrity at high pressure.
- Results support plans to extend life until 2028.



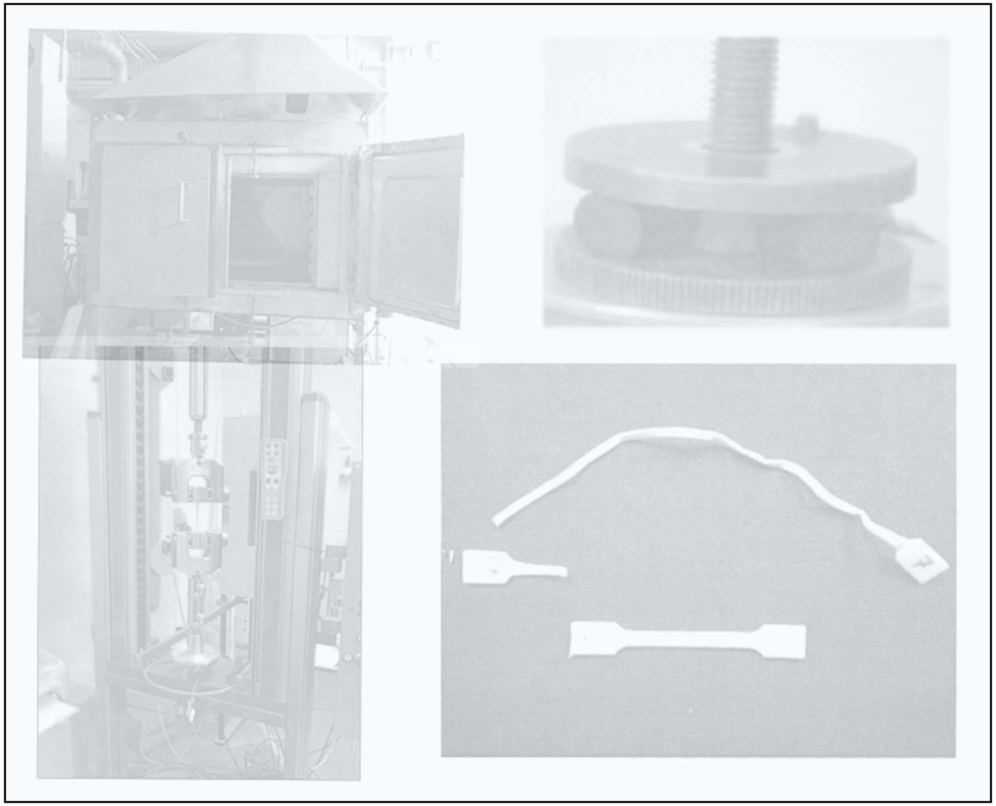
Compressor Assembly

- FGB has 3 functionally redundant compressors housed in a pressure tight nitrogen chamber.
- Classified as Active but Non-Critical (AN) component based on SLE optimization

- Ground test unit was used to simulate flight like operations
- Original certification covers cycle life until 2028
- Heat exchanger materials assessed for long term exposure to Triol coolant.
- Soft goods test provides basis for extending service lives of components within the compressor assembly
  - Pressure reducer, check valve, safety valve, electro-pneumatic valve,…

Soft Goods

- Accelerated aging of representative coupons from multiple components
- Seals and O-rings in deformed and non-deformed state
- Test conditions derived from proprietary statistical and probabilistic models
- Thermal chamber for heating coupons to 343 K for 30 days.
- Pressure tight containers for high pressure application.
- Hydraulic press to measure strain and strength properties.
- Contact stress relaxation determined using axial compression relaxation instrument



- Results provide basis for extending service life until 2028.

Summary

- The FGB is the first element of the ISS, built in Russia under a U.S. contract.
- Original certification for FGB operations expired in 2013.
- Efforts to extend the FGB service life until 2028 are discussed.
- Project adopted methods to
  - ➢ Identify the life limiting components
  - ➢ Optimize the SLE efforts based on hazard analysis, failure modes/criticality analysis and validation requirements
  - ➢ Devise and execute a comprehensive, multipronged test and analysis campaign
  - ➢ Integrate the results and provide expert assessment
- Results provide the basis for extending the service life of FGB propulsion system until 2028.

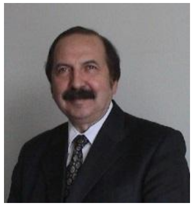
Authors

ULHAS KAMATH *is a Senior Technical Lead at Boeing-Houston, responsible for Systems Integration of the International Space Station Propulsion Systems and is involved in the formulation and development of architectures for Human Space Exploration beyond Low Earth Orbit. Prior to ISS, he supervised the design, development, testing, analysis and operations of communications satellites at Intelsat of Washington, DC and the Indian Space Research Organization. He holds a bachelor's degree in Mechanical Engineering from University of Mysore, a Ph.D. in Aerospace Engineering from Indian Institute of Science, and an MBA from University of Houston-Clear Lake.*

GREGORY GRANT *is the FGB Service Life Extension Project Manager for the International Space Station. The project scope encompasses the extension of operational service life of the FGB module non-replaceable subsystems and structural elements, as well as developing diagnostics methods for predicting failures and providing spare subsystem components. Prior to this work he was involved in supervising the production, testing, and on-orbit checkouts of the FGB module. He holds a bachelor's degree in Aerospace Engineering from the Texas A&M University.*

SERGEI KUZNETSOV *is a Head of department responsible for development, testing and exploitation of spacecrafts and launchers propulsion and thermal control systems at Khrunichev Space Center. Participated in works on the FGB propulsion and thermal control systems life extension until 2028. Being at different positions, participated in new developments of propulsion and thermal control systems in the frames of both Khrunichev and foreign customers projects. In 2000 graduated from Moscow Aviation Technology University and received a specialization "aviation engines and power systems".*

Authors



SERGEY SHAEVICH *is the ISS Program Director at Khrunichev Space Center since 1994 until now. Being at different positions, from designer to head of design and development department, participated in development and creation of manned long-term stations "Salyut", heavy transport vehicles "Kosmos" and modules of "Mir" station and in development and creation of the ISS first element FGB "Zarya" as the ISS Program Director.* In 2014 managed *a work on the FGB Life extension until 2028 with regard to non-replaceable equipment. In 1968 graduated from Bauman Moscow Technical University and received a degree "mechanical engineering". In 2000 defended his Ph.D. Degree in the area of space hardware design and development. Dr. Shaevich is an author of 28 published works and more than 30 patents in the area of rockets and space science.*

VICTOR SPENCER *is the Propulsion System Manager for the International Space Station for NASA and is also working with commercial partners to design and develop the next generation of human launch vehicles. Prior to working on the ISS project, he was involved in working on the maintenance and design of new propulsion upgrade hardware for the Space Shuttles, and prior to that, the concept and design of both lunar and Mars human landing and ascent propulsion systems. In addition to his 22 years in the Propulsion Division at Johnson Space Center, he has also done work tours in both the Safety and Mission Assurance and the Manufacturing and Design Divisions at NASA. Mr. Spencer holds a bachelor's degree in Aerospace Engineering from the Wichita State University.*